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# Yield response of potato to spatially patterned nitrogen application

Rose M. Shillito[a], Dennis J. Timlin[b,*], David Fleisher[b], V.R. Reddy[b], Bruno Quebedeaux[a]

[a] Department of Plant Science and Landscape Architecture, University of Maryland, College Park, MD, United States
[b] USDA-ARS Crop Systems and Global Change Laboratory, Building 001, Room 324, 10300 Baltimore Avenue, Beltsville, MD 20705, United States

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ABSTRACT

Although crop response to nitrogen fertilization has long been studied, classical experimental designs have led to inadequate accounting of spatial variability in field properties and yield response. Analytical methods to explicitly account for spatial variability now exist but the complementary modification of experimental design is still developing. There is a need to combine these analytical methods with non-traditional experimental design. A 2-year study was implemented to assess the response of potato (*Solanum tuberosum* cv. Kennebec) yield to nitrogen fertilizer rate. We used a transect-type plot design where four nitrogen treatments (0, 56, 112, and 280 kg N ha$^{-1}$) were applied systematically in a continuous sinusoidal pattern along longitudinal transects. Measured field properties included topography, soil texture, pre-application soil nitrate levels, and plant available soil water content. A random field linear model was used to simultaneously account for treatment effects and soil properties. The results showed that treatment effects were significantly different from each other; however, if spatially correlated errors were accounted for, these differences were smaller and significance levels lower. Nitrogen response functions varied widely throughout the field. Of the covariates, only clay content proved important in explaining spatial differences in response to N. The sinusoidal response pattern of N was similar over the 2 years but the amplitudes varied due to differences in weather. Interactions between uncharacteristically high rainfall and a sandy field soil may have minimized discernable effects of the other covariates. The results demonstrated how the statistical analysis of potato response to a patterned application of nitrogen fertilizer can take advantage of spatial correlations to understand the response of potato to nitrogen application over larger areas.

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## 1. Introduction

It is estimated that nitrogen use efficiency (NUE) for agriculture globally ranges from 10 to 50%, indicating that more than half the applied N is lost to the plant and the immediate crop environment (Mosier et al., 2004). The largest N losses and the lowest NUEs tend to occur in highly industrialized countries where the low cost of N lends itself to excessive fertilization. Not only are costs associated with low efficiency, but the effects of N dispersed in the wider environment can lead to serious environmental and ecologic consequences (Matson et al., 2002). While there has been some increase in NUE in the United States, Cassman et al. (2002) point out that the major impediment to realistic improvement is the lack of understanding "of plant response to spatial and temporal variations in soil conditions." Specifically, Dobermann and Cassman (2004) claim that research results have not been translated properly into farming practice because little use has been made of spatial information in discrete plot-based research; thus, extrapolation to farm-scale operations is compromised. In a review of the current literature, Balasubramanian et al. (2004) show mean NUE of research plot results are consistently higher than mean NUE under current farming practices for several major crops.

Nitrogen as nitrate is primarily found as a solute dissolved in soil water. Since water fluxes in soil can be highly variable from location to location, the transport of N with water is also variable. This can result in spatial variability of N availability in the soil that can result in spatial differences in N response (Scharf, 2001; Bélanger et al., 2000a). The economically optimum N response rate from N response curves varies from field to field and within fields having different optimums and correlation scales (Scharf et al., 2005). These variations in the spatial structure of N response suggest strong linkages to soil properties such as topographic variables, e.g., slope and curvature (Timlin et al., 1998; Pachepsky et al., 2001; Shahandeh et al., 2005.

The majority of agronomic experimentation and inferential statistical techniques used to analyze field experimental data are

* Corresponding author. Tel.: +1 301 504 6255; fax: +1 301 504 5823.
*E-mail address:* dennis.timlin@ars.usda.gov (D.J. Timlin).

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based on the assumption of statistical independence and use blocking and replicates to minimize or remove the (nuisance) effect of spatial variability and maximize the efficiency of sampling number. But, spatial variability in field response variables or covariates are seldom randomly distributed and usually display some patterning. Blocking, too, has come under scrutiny within the context of spatial variability, especially if the assumption of within block heterogeneity is not checked or met (Gusmão, 1986; Mulla et al., 1990; Lin et al., 1993). Hong et al. (2005) showed blocking to be ineffective in some circumstances when spatial variability is otherwise accounted for. Ultimately, the effect of spatial variability when using conventional statistical analyses is that treatment effects and locational effects are often indistinguishable (Heffner et al., 1996), and that the correct probability of Type I and Type II errors is obscured (van Es and van Es, 1993; Legendre et al., 2002), as is the ability to extrapolate from discrete plots to whole-field response. Mulla et al. (1990) using nearest neighbor analysis showed that yield means, thus treatment effectiveness, were sensitive to spatial variability in potato.

Peterson et al. (1993) stated that there is a need to move away from small-plot research toward more field-scale experimentation across soil and climatic gradients. The incorporation of a landscape approach will not only help to better understand crop response, but also to increase applicability of results. In a recent review of the design and analysis of agronomic experimentation during the past 100 years, Edmondson (2005) stated that future emphasis will be on the design of spatially efficient experiments since computational intensity is no longer an impediment. Nielsen and Wendroth (2003) question the need for discrete treatment experimentation when techniques exist to analyze more realistic continuously varying treatments across a gradually changing landscape. Gotway and Cressie (1990) showed that analysis of variance methods could be used to test treatment effects by correcting the variance–covariance structure of a linear model for spatial dependence through the use of geostatistical semivariogram functions. Zimmerman and Harville (1991) advocated the direct modeling of spatial correlation and provided a rigorous development of the above analysis they called the random field linear model (RFLM). The general form of the RFLM included a fixed (mean) component, a random (e.g., blocking) component (optional), and a correlated error structure. They used restricted maximum likelihood methods for parameter estimation, and showed that RFLM methods to assess treatment effects within the context of spatial variability provided more appropriate variance estimates than nearest neighbor analysis. Brownie and Gumpertz (1997) confirmed the development of Zimmerman and Harville (1991) and concluded that gains in statistical efficiency in spatially correlated error analysis over classical statistical approaches did not sacrifice statistical validity. The work by Zimmerman and Harville (1991) provided the basis for the development of spatial analysis in the SAS PROC MIXED statistical package (Littell et al., 1996).

The use of RFLM in agricultural experimentation is recent and increasing. To assess the effects of soil and fertilizer on corn yield, Hoosbeek et al. (1998) concluded the RFLM approach supplied better predictors than kriging alone as explanatory variables could be explicitly assessed. The usefulness of the RFLM to extrapolate from plot to field scale was highlighted. In a study of sugar-cane yield variability, Anderson et al. (1999) commented on the usefulness of the RFLM to account for spatial variability and still allow for inference testing. Singh et al. (2003) tested several classical models (e.g., complete/incomplete block design) with and without spatially correlated errors on three crops (chickpea, lentil and barley) and found that accounting for spatially correlated errors was more critical than model structure in assessing total variability in field trials. Eghball et al. (2003) used RFLM to adjust corn yield means for spatial variability in a multifractal analysis of variable rate nitrate management. RFLM studies have proven particularly amenable to precision agriculture. Griffin et al. (2005) used RFLM to assess yield-monitor data for whole-field applications and concluded the RFLM provided efficient and unbiased estimates regardless of replication. Recently, Hong et al. (2005) provided a thorough methodological development and application procedure.

Few studies have utilized patterned application of treatment variables specifically to quantify the effects of spatial variability on response functions. Fox (1972) was one of the first to carry out a field study where fertilizer application rates were imposed in a gradually increasing rate along a transect as an alternative to using small randomized plots. Citing this study as an example, Nielsen and Wendroth (2003) recommended alternative approaches to impose treatments such that variation in response functions can be understood and quantified with respect to the entire field. The objectives of the research presented here were to: (a) quantify the spatial response of potato yield to four levels of a nitrogen fertilizer applied in a sinusoidal spatial pattern on a (134 m $\times$ 14 m) field as suggested by Nielsen and Wendroth (2003), and (b) to quantify the effects of continuously variable soil properties (soil texture, initial nitrate content and water holding capacity) on the resultant yield pattern. This will allow for the presentation of a yield response function over a large heterogeneous area (Cassel et al., 1988; Hoosbeek et al., 1998; Sadler et al., 2002) and induce a known spatial yield pattern over presumably unknown distributions of field properties. Ultimately, we will show that it is possible to exploit the spatial relationships inherent in yield data and in correlated soil properties to extrapolate whole-field responses to nitrogen application.

## 2. Materials and methods

### 2.1. Experimental design and site characteristics

The field experiment was conducted in 2003 and 2004 at the Henry A. Wallace Agricultural Research Center, Beltsville, Maryland (BARC). The research center is located at 39.03472 latitude, −76.90778 longitude. Average monthly temperature for April to August (inclusive) is 20.4 °C, where July is typically the warmest month. Average monthly precipitation for the same period is 91 mm, or a total of 455 mm for the period, which accounts for approximately 40% of the average annual precipitation.

The experimental field measured approximately 134 m $\times$ 14 m (0.18 ha) (Fig. 1). The majority of the field was classified as Downer-Ingleside loamy sands (coarse-loamy, siliceous, mesic Typic Hapludults [Haplic Acrisols, FAO]). The soils at the north and south ends of the field were classified as Matawan and Keyport series (fine-loamy, siliceous or mixed, mesic Aquic Hapludults [Gleyic Acrisols, FAO]). Each year, the Farm Management Unit at the research center collects a composite of 10–12 soil samples from the surface 10 to 15 cm for nutrient analysis (nitrogen (N), phosphorous (P), potassium (K), OM and pH). Based on soil tests for the past 8 years, the organic matter content of the surface soil varied from 0.9 to 1.3 g kg$^{-1}$ and the pH from about 5.7 to 6.1. The phosphorus content was generally high and potassium moderate. The field was fertilized accordingly at pre-plant. A rye (*Secale cereale*) winter cover crop was planted in the field prior to both the 2003 and 2004 experiments. The rye was mechanically plowed under while chiseled and disked during field preparation prior to planting. The field had been planted with vegetables followed by a winter rye cover crop for the 3 years preceding the 2003 experiment. Field topography was sampled via a real-time kinematic GPS survey at an approximate spacing of 1 point per 2.7 m.

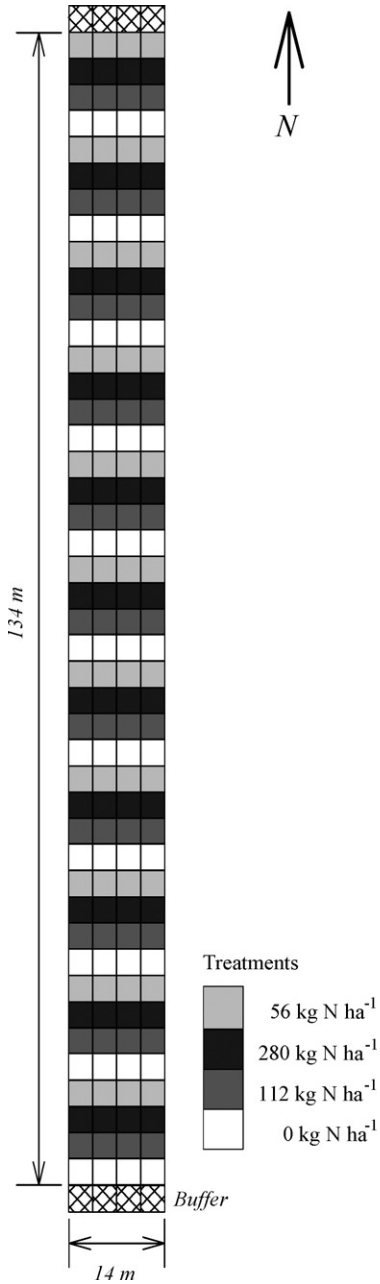


**Fig. 1.** Experimental field dimensions and treatment layout.

The field experimental design consisted of four parallel, adjacent longitudinal transects, each 132 m long. Each transect contained 44 consecutive 3 m × 3 m experimental plots (Fig. 1): for a total of 176 plots. A single 15 cm deep × 2 cm diameter soil sample was collected from the center of each 3 m × 3 m plot and was analyzed for soil texture and initial nitrate contents on the 4 transects (a total of 176 samples). The soil was sampled on 20 May 2003 and 02 May 2004. These dates were after plant emergence but before hilling and N fertilization. Surface soil (0–15 cm) particle size distribution was determined via the hydrometer method (Gee and Bauder, 1986). The soil samples were dried before analysis. Soil nitrate concentrations were determined by cadmium reduction method (Mulvaney, 1996) at the University of Maryland Soil Testing Laboratory (College Park, MD, USA). As no ammonium fertilizer was applied and the soil had low organic matter content, we did not measure ammonium forms of N in the soil. Additional undisturbed surface soil cores were collected from the center of each of the 44 plots in a single, central transect in order to estimate the plant available soil water content (PAWC). The variability of soil texture as a function of the short distance between transects was not large so we did not sample all four transects. These cores measured 5.4 cm in diameter × 6 cm in length and sampled the 0–15 cm depth that was well mixed by tillage. Soil water characteristic curves were developed for each core using a pressure plate apparatus. PAWC was determined as the difference between volumetric water contents ($cm^3\ cm^{-3}$) at matric potentials of −0.01 and −1.5 MPa, as recommended for sandy soils (Hansen et al., 1980; Or and Wraith, 2002).

The field was planted with potato (*Solanum tuberosum* L. cv. Kennebec) in rows spaced at 0.76 m; average plant spacing was 0.38 m. The rows were aligned parallel with the transects. Plant density was 32 plants per unit or 3.6 plants $m^{-2}$. The soil was fertilized pre-plant with P and K but not N. Potatoes were planted on 23 April 2003 and on 22 April 2004 (DOY 113 in both years). Potatoes were not irrigated in either year as frequent rainfall events precluded extended dry periods (maximum number of consecutive days without rainfall was 5 days in 2003 and 6 days in 2004). A 3-m buffer at both the south and north ends of the field was also planted with potatoes, but was excluded from analysis, as were single buffer rows of potatoes along the longitudinal edges of the field.

The nitrogen fertilizer treatments were applied on 2 June 2003 (DOY 153) and 26 May 2004 (DOY 147); this corresponded to 22 and 17 days after 50% emergence in 2003 and 2004, respectively. Each nitrogen fertilizer treatment was applied manually across the entire width of the field (i.e., perpendicular to the transect, Fig. 1). The nitrogen fertilizer was in the form of calcium nitrate granules and was applied only once during the growing season in the same pattern and at the same location both years. The fertilizer was broadcast by hand and incorporated into the soil during a mechanical hilling operation that immediately followed application. The nitrogen treatment units varied longitudinally along the entire length of the field in a sinusoidal pattern. The order of application (south-to-north) was 0, 112, 280, then 56 kg N $ha^{-1}$. This pattern was repeated 11 times along a transect (Fig. 1). Treatment levels were chosen to elicit a range of yield responses around the recommended nitrogen fertilizer application rate for the area (about 112 kg N $ha^{-1}$), and to minimize large differences in N application between adjacent treatments. The nitrogen fertilizer treatment pattern was designed to more realistically represent a continuous and gradually varied treatment application, and to induce a known spatial yield pattern over presumably unknown distributions of field properties.

The number of nodes on two plants in the center of each 3 m × 3 m plot was counted three times during the growing season (on a total of four transects). This count allowed the calculation of the average node addition rate (growth rate) for the period between emergence and fertilization. Weeds were controlled by cultivation immediately following fertilizer application, and later, by hand. Insects and diseases were controlled with two spray applications each year.

The potato tubers were harvested on 19 August in 2003 and on 18 August in 2004—118 days after planting. Above ground growth was removed, and potatoes were uncovered with a two-row digger attached to a tractor, with tractor direction reversing in alternate transects to mitigate possible yield bias. The harvest included all potatoes from the two center rows of each 3 m × 3 m unit (there were a total of four rows in each unit). Total count and weight of potatoes per unit were recorded immediately after collection. In both years, only the two middle transects were harvested for a total of 88 plots.

The field properties examined include: elevation, sand content, clay content, initial soil nitrate (prior to fertilizer application) concentration, PAWC and yield. Except for PAWC, all soil properties were measured in each 3 m × 3 m unit on four transects (total of 176 plots). The soil data from two neighboring transects were aggregated. A basic assumption for this research is that physical and hydraulic field properties (topography, soil texture, PAWC) were constant with time. The rooting depth of this soil is restricted by a hardpan at approximately 35–40 cm in depth. Previous studies have shown little root activity below this depth.

### 2.2. Statistical analysis

Treatment effects were assessed through the use of random field linear models (Zimmerman and Harville, 1991) as implemented by SAS PROC MIXED (Littell et al., 1996). The general linear mixed model is

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u} + \mathbf{e} \tag{1}$$

where **y** is the vector of observations, **X** the treatment design matrix, $\boldsymbol{\beta}$ the vector of treatment fixed effect parameters, **Z** the block design matrix, **u** the vector of random block effects, and **e** the vector of experimental errors. Var(**y**) = var(**e**) = **R**, the covariance matrix of **e**. Since the data were effectively contiguous, no blocking was necessary in this study and the **Zu** term was eliminated. Treatment effects, significant covariates and interactions alone determined the mean structure, $\mathbf{X}\beta$. PROC MIXED allowed for several covariance structures, among them, a subset of two-dimensional spatial structures based on geostatistical variogram parameters—a partial sill, range, and nugget, where the partial sill and nugget together comprised the variance of the observations. Thus, the spatial component of the statistical analysis applied only to the error covariances, not to the mean structure.

The mean model parameters were developed via backward elimination using maximum likelihood (ML) estimates (Littell et al., 1996; Hong et al., 2005), such that intercepts and slopes were significant ($P < 0.05$). An initial spatial covariance structure was chosen, then the mean model was determined by removing non-significant terms one at a time. Several spatial covariance structures were then tested, the final model selection based on minimized Akaike's Information Criteria (AIC) for the whole model. A spherical covariance structure with a nugget was selected as the final spatial covariance structure. The 2 years of data were not pooled for initial analysis since it was not expected that the results would be similar. Spatial interpolation for N response yield maps was accomplished via kriging (Golden Software, 2002) using spatial variability parameters determined from PROC MIXED.

## 3. Results and discussion

### 3.1. Weather

Precipitation and average daily temperature data for the 2003 and 2004 April–August growing seasons are shown in Fig. 2. Total precipitation for the period was 522 mm in 2003 and 509 mm in 2004, with 2003 being the wettest year on record for the region. However, early growing season (DOY 130–170) temperatures in 2003 differed markedly from those in 2004. The average daily temperature for that period in 2003 (16.3 °C) was notably lower than in 2004 (22.2 °C). Additionally, while the number of rainy days (events) for that period was similar (27 and 21 days for 2003 and 2004, respectively), the amount of precipitation per event in 2003 (10.0 mm) was almost double than in 2004 (5.1 mm). For both years, this period corresponded to time of emergence until approximately 20 days after nitrogen fertilizer application.

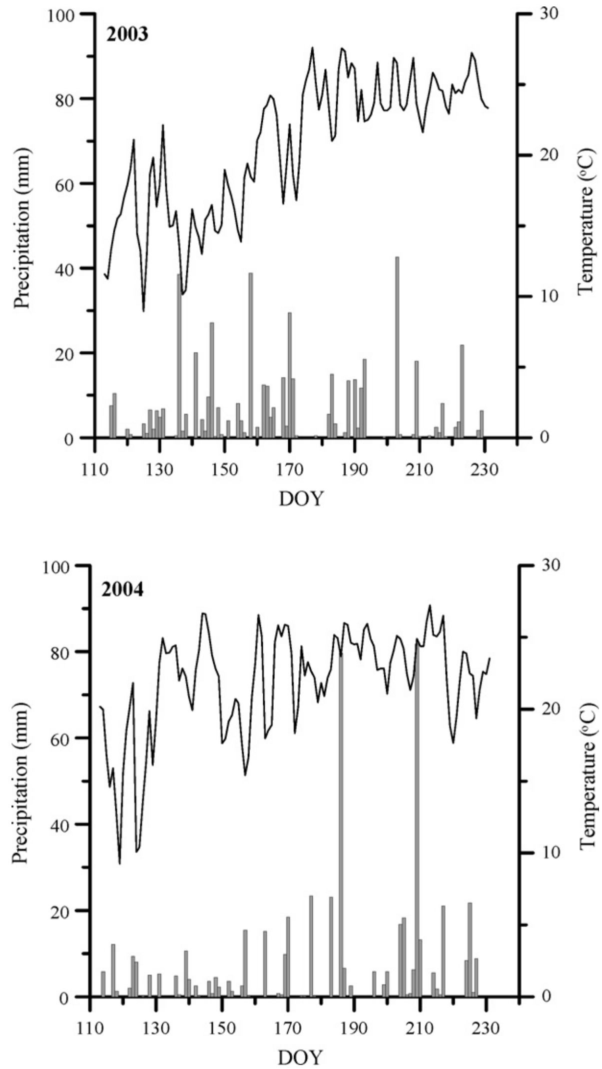


**Fig. 2.** Precipitation (bars) and temperature (lines) during the growing season for 2003 and 2004.

### 3.2. Field properties

Basic descriptive statistics for field properties appear in Table 1. The amount of variability in these field properties was within or below ranges typically recorded in the literature (Mulla and McBratney, 2002). The distribution of measured field properties as a function of location is shown in Fig. 3. The high elevation point lies near the center of the field. From the center, the decrease in elevation was constant, with the south-facing slope (0–70 m) somewhat less steep (1% slope) than the north-facing slope (about

**Table 1**
Descriptive statistics of field properties

| Field property (units) | *N* | Mean | CV (%) | Range |
|---|---|---|---|---|
| Elevation (m) | 246 | n/a | 2.2 | 15.6–16.9 |
| Sand (g $kg^{-1}$) | 176 | 794.7 | 2.4 | 762.5–830.0 |
| Clay (g $kg^{-1}$) | 176 | 105.7 | 6.1 | 92.5–117.5 |
| PASW ($cm^3$ $cm^{-3}$) | 44 | 0.057 | 20.9 | 0.006–0.029 |
| Initial soil N, 2003 (mg $kg^{-1}$) | 176 | 4.9 | 29.3 | 3.0–9.6 |
| Initial soil N, 2004 (mg $kg^{-1}$) | 176 | 2.0 | 27.8 | 1.2–4.4 |

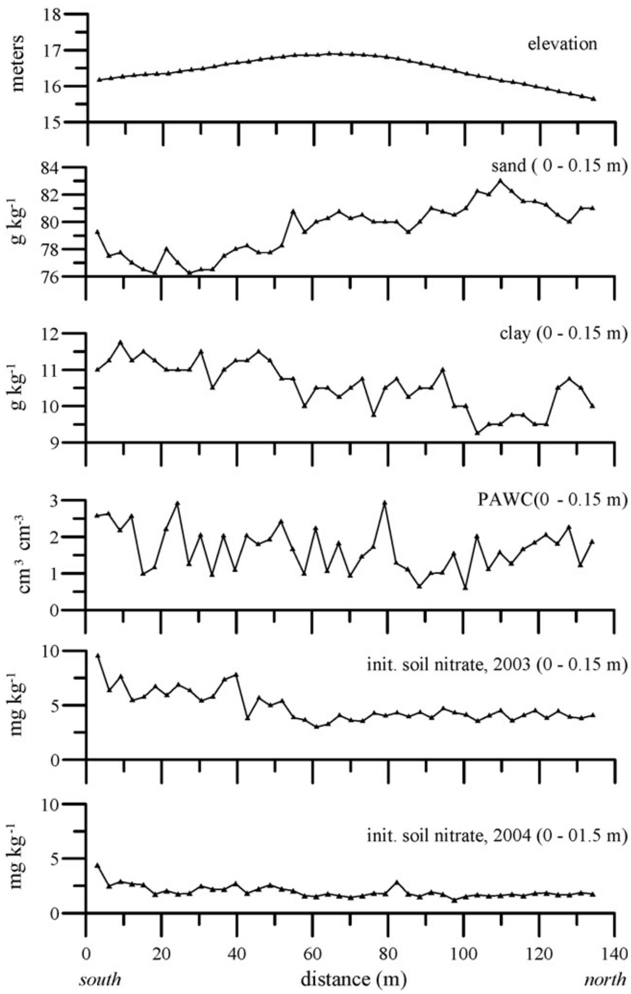


**Fig. 3.** The distribution of collected data over the experimental field.

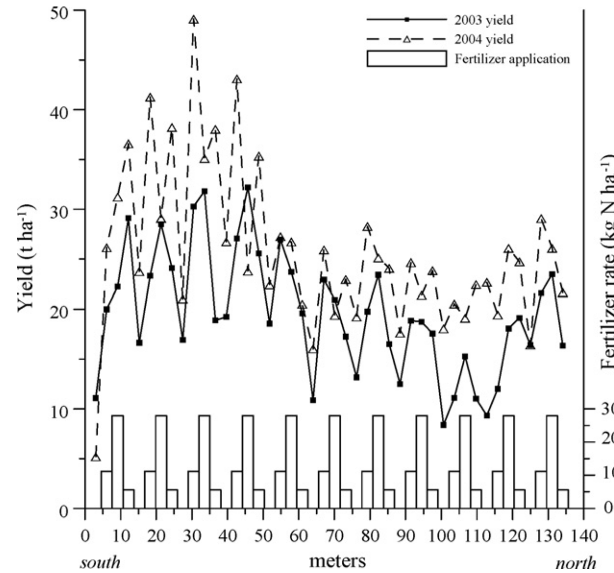


**Fig. 4.** Potato yield (t ha$^{-1}$) for 2004 and 2004. The nitrogen application rates were 0, 112, 280, and 56 kg N ha$^{-1}$. The nitrogen application pattern was the same for both years.

2%). The maximum elevation difference was 1.6 m. There was no evidence of major surface flow features due to topography (erosion or deposition), except that standing water was evident at the south end of the field following large rainfall events, possibly due to the lack of drainage from the field to the surrounding slightly raised grass buffer. Surface soil (0–15 cm) sand and clay contents exhibited nearly mirror trends across the field with a relatively high clay content and a low sand content at the south end of the field. Clay content reached a maximum, and sand content a minimum, between 100 and 120 m, near the north end of the field. There was no discernable pattern in the field distribution of PAWC in the surface 0.15 m of soil.

Initial soil nitrate distributions for both 2003 and 2004 also appear in Fig. 3. Initial soil nitrate concentrations in 2003 were double those in 2004, possibly due to previous experimental treatments. There was no evidence of the 2003 sinusoidal nitrogen application pattern in the 2004 pre-treatment soil nitrate distribution. Thus, the 2003 potato crop and water transport processes were effective at removing (through uptake or leaching) excess soil nitrate from the field, eliminating the possibility of any spillover effect between the 2003 and 2004 experiments.

### 3.3. Potato yields

Potato yields for the 2003 and 2004 seasons are shown in Fig. 4. Potato yields in 2003 were consistently less than in 2004, but the transect-scale pattern of yield response was consistent both years. In both years, the highest yields occurred in the south part of the field (0–50 m) and lowest yields in the north part of the field (80–130 m). The pattern of yield for both years reveals a periodic response to the sinusoidal N application rate. The yield response to fertilizer application exhibited the same pattern in that the response to fertilizer application was greater in the south part of the field where the sinusoidal pattern was amplified. Yield response to fertilizer application was attenuated in the north part of the field for both years.

Yield means as a function of N treatment only are shown in Fig. 5A, where the data were fitted with a quadratic yield model (Bélanger et al., 2000b). The 2003 yield data exhibited a quadratic-plateau response to fertilizer treatment. The 2004 means were higher and exhibited a peaked then decreasing response to the highest N treatments. The difference in yield response between the 2003 and 2004 seasons was apparent. In 2003, means from the two highest treatments (112 and 280 kg N ha$^{-1}$) did not differ from each other, but were distinct from the lower N treatments. In 2004, the highest-yielding 112 N treatment appeared different from the 56 and 280 treatments. In both years, the 0 N treatments were different from all other treatments for that year. But, these results did not consider spatially correlated errors.

#### 3.3.1. Weather effects

Experimental design, planting, treatment application, and crop management were replicated as much as possible in 2003 and 2004, therefore the difference in annual potato response is noteworthy. The difference in early season temperatures noted earlier may partially explain this difference. From node counts gathered throughout the field during both growing seasons, the node addition rate for the pre-application period was 0.57 nodes day$^{-1}$ in 2003 and 0.76 nodes day$^{-1}$ in 2004. Since node addition is not a function of soil nitrogen status (Vos and Biemond, 1992) but rather a function of temperature (Struik and Ewing, 1995; Firman et al., 1995), we believe the 2004 plants were larger and able to access and use N in the soil. Furthermore, since lower temperatures early in the growing season coincided with more precipitation in 2003, we believe the mobile N fertilizer was leached or dissipated beyond the plant roots that were growing too slowly to efficiently capture the N. In the comparatively drier early growing season in

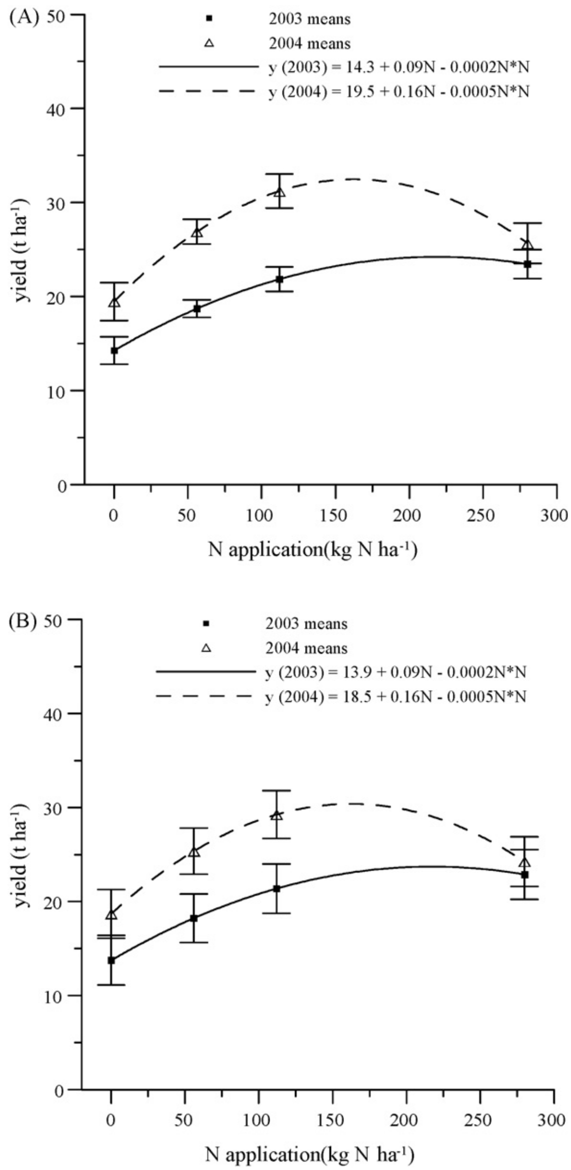


**Fig. 5.** Nitrogen response curves (A) without and (B) with spatially correlated errors. Symbols indicate means and bars indicate standard errors.

2004, possibly more N was available for plant growth, so much in fact, that tuber growth was adversely affected by the highest N treatment. In a review of potato nitrogen management, Alva (2004a) noted that excessive N contributed to excess potato vine growth at the expense of tuber production. No beneficial effect on tuber growth occurred in N applications beyond 336 kg N ha$^{-1}$ in irrigated fields on fine sandy soils (Alva, 2004b).

*3.3.2. Impact of spatial variability*

Yield means calculated with spatially correlated errors are shown in Fig. 5B. The general forms of the yield responses for both years are similar; however the significance of treatment means was altered. In 2003, only the 280 N treatment was distinct from the 0 N treatment; in 2004, the 112 N treatment was different from the 0 N treatment. For both years, the only clear treatment effect was between the maximum yielding treatment and the 0 N treatments. Overall, treatment means were less distinct from each other due to expanded standard errors which resulted from accounting for spatially correlated errors. Spatial correlation in data acts as a variance inflation factor (Griffith and Layne, 1999) or, alternatively, essentially reduces the sample size (Matalas and Langbein, 1962; Clifford et al., 1989). Thus, Fig. 5B more accurately reflects the true means and variances associated with the field data.

*3.3.3. Effects of secondary variables*

The RFLM was used to further explore yield response to treatments and field soil characteristics. The soil characteristics examined included clay content, initial soil nitrate concentration, and PAWC. Each year was analyzed separately. The only field characteristic that proved significant in describing yield data was clay content (Table 2). Nitrogen × clay and nitrogen × nitrogen × clay interactions were significant both years verifying the quadratic yield response. The presence of two additional terms in the 2004 field response indicated a slightly more complicated clay effect that year. AIC values were lower for the spatial treatment models including clay than the treatment-only spatial models both years indicating a positive effect of clay

**Table 2**
Coefficients and standard errors for three RFLM models each for the 2003 and 2004 yield data

| Model and model effects | Estimate | Standard error | AIC[a] |
|---|---|---|---|
| Treatment only—2003 | | | 296.3 |
| Intercept (kg N ha$^{-1}$) | 14.3*** | 1.45 | |
| Nitrogen (kg N ha$^{-1}$) | 0.09** | 0.03 | |
| Nitrogen × nitrogen (kg N ha$^{-1}$)$^2$ | −0.0002* | 0.0001 | |
| Residual error (t ha$^{-1}$)$^2$ | 25.9*** | 5.71 | |
| Treatment only—2004 | | | 323.3 |
| Intercept (kg N ha$^{-1}$) | 19.5*** | 2.02 | |
| Nitrogen (kg N ha$^{-1}$) | 0.16*** | 0.04 | |
| Nitrogen × nitrogen (kg N ha$^{-1}$)$^2$ | −0.0005*** | 0.0001 | |
| Residual error (t ha$^{-1}$)$^2$ | 49.93*** | 11.03 | |
| Treatment only + spatial errors—2003 | | | 267.7 |
| Intercept (kg N ha$^{-1}$) | 13.8* | 2.84 | |
| Nitrogen (kg N ha$^{-1}$) | 0.09*** | 0.02 | |
| Nitrogen × nitrogen (kg N ha$^{-1}$)$^2$ | −0.0002*** | 0.0001 | |
| Cov. nugget (t ha$^{-1}$)$^2$ | 6.17** | 2.23 | |
| Cov. range (m) | 66.03* | 34.70 | |
| Cov. partial sill (t ha$^{-1}$)$^2$ | 23.63 | 16.88 | |
| Treatment only + spatial errors—2004 | | | 307.3 |
| Intercept (kg N ha$^{-1}$) | 18.4* | 3.16 | |
| Nitrogen (kg N ha$^{-1}$) | 10.2*** | 0.03 | |
| Nitrogen × nitrogen (kg N ha$^{-1}$)$^2$ | −0.0005*** | 0.0001 | |
| Cov. nugget (t ha$^{-1}$)$^2$ | 19.2*** | 6.18 | |
| Cov. range (m) | 50.0* | 27.95 | |
| Cov. partial sill (t ha$^{-1}$)$^2$ | 32.85 | 24.16 | |
| Treatment + clay + spatial errors—2003 | | | 275.1 |
| Intercept (kg N ha$^{-1}$) | 13.8* | 2.64 | |
| Nitrogen × clay (kg N ha$^{-1}$) | 0.01*** | 0.0015 | |
| Nitrogen × nitrogen × clay ((kg N ha$^{-1}$)$^2$* %) | −0.0002*** | >0.0001 | |
| Cov. nugget (t ha$^{-1}$)$^2$ | 6.2* | 2.15 | |
| Cov. range (m) | 66.1* | 36.17 | |
| Cov. partial sill (t ha$^{-1}$)$^2$ | 20.1 | 14.79 | |
| Treatment + clay + spatial errors—2004 | | | 319.4 |
| Intercept (kg N ha$^{-1}$) | 18.7** | 2.59 | |
| Nitrogen (kg N ha$^{-1}$) | −1.2*** | 0.31 | |
| Nitrogen × clay (kg N ha$^{-1}$) | 0.12*** | 0.03 | |
| Nitrogen × nitrogen (kg N ha$^{-1}$)$^2$ | 0.004*** | 0.001 | |
| Nitrogen × nitrogen × clay ((kg N ha$^{-1}$)$^2$* %) | −0.0004** | 0.0004 | |
| Cov. nugget (t ha$^{-1}$)$^2$ | 11.7** | 4.4 | |
| Cov. range (m) | 41.1* | 20.2 | |
| Cov. sill (t ha$^{-1}$)$^2$ | 26.9 | 17.8 | |

* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.
[a] Akaike's information coefficient.

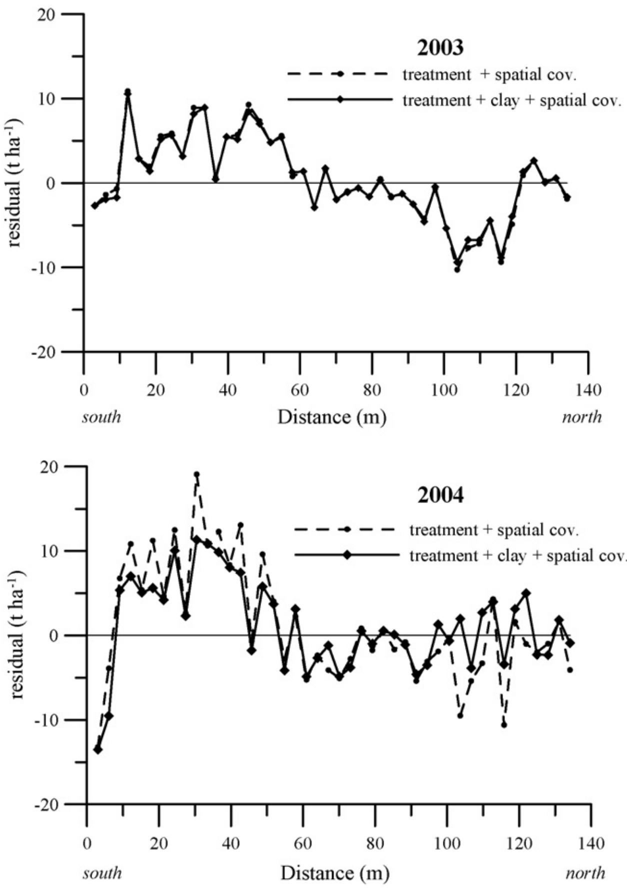


**Fig. 6.** Model residuals (observed-predicted) as a function of distance along the transect.

content on crop yield. Initial soil nitrate content or PAWC were not significantly associated with yield in either year.

The spatial distribution of the treatment model residuals were examined to further assess the effect of correlated soil properties on yield (Fig. 6). In 2003, clay had the effect of only very slightly bringing means closer to zero. The effect was more pronounced in 2004. While residuals in the south part of the field were reduced, the residuals in the north end of the field, where clay content was lowest, were brought much closer to zero. Although the undistributed residuals may cluster close to zero, the persistence of undulating trends in the within-field residuals in Fig. 6 indicate that other spatially varied field properties (e.g., CEC, soil pH and soil organic matter) that were not measured may have some explanatory effect on yields.

Statistically, the effect of clay was somewhat marginal. Functionally, the effect of clay may have been important as a spatial covariate insofar as clay content represented a soil particle size class important to the water flow and nitrate transport processes in a soil that affects plant growth throughout a growing season. Shahandeh et al. (2005) noted that soil mineral N was significantly correlated with clay content in both years of their study. These results for soil texture were similar to block-kriged results reported by Redulla et al. (2002). In a study of four fields over a 3-year period, soil texture was the only consistently significant field parameter associated with potato yield; soil chemical properties (e.g., soil nitrate, CEC and pH) proved significant only sporadically. It should be noted that sand and clay contents were inversely correlated–increasing sand content decreased response to the N treatment–but clay proved the more significant covariate. We did not measure pH or organic matter for individual plots; these may have also influenced the response to nitrogen.

There was no significant effect of pre-plant N. Errebhi et al. (1998) and Alva (2004b) reported that pre-plant (initial) soil N concentrations were not significantly associated with increased tuber yield. According to Vos (1999), there is little or no uptake of N in potatoes 28–42 days after planting, and after about 60 days after emergence. Thus, for the 2003 and 2004 potato experiments, soil nitrate measured anytime after fertilizer application and up to DOY 191 may have been more significantly related to potato yield. Bélanger et al. (2001) reported that, in potato, the N requirement could not be predicted from pre-plant N in a sandy soil in the upper St. John River Valley of New Brunswick, Canada. There was also no significant effect of water availability. PAWC is a measure of the water holding capacity of a soil—a capacity which was most likely adequately filled for potatoes during the wet 2003 and 2004 growing seasons. A measure of the water holding capacity of a soil may be a more significant covariate during dry years (Timlin et al., 2001).

### 3.4. Scaling from plot to field

In plot research, the plot response is measured but whole-field response is inferred. Generally, only the fixed effects of treatment response are of interest to the researcher. The effects of (random) error are used to determine the degree of confidence one would have in the fixed effects results but otherwise are not of interest for extrapolation of the results. In agricultural landscapes, however, the seemingly random effects often have a correlation structure and patterns that can be captured by calculating error as a function of distance between measurements and possibly related to other landscape and soil features. This is known as regionalized variable theory (Matheron, 1963). Hoosbeek et al. (1998) utilized a combination of modeling fixed fertilizer treatments and ordinary kriging to interpolate yield response from blocked plot data to field scale. Similarly, Cassel et al. (1988) used kriging to scale up corn yield response to tillage treatment from strip plots to the entire field. In both cases, knowledge of the spatial variation in mean response was used to spatially adjust the means from the fixed effects model for location in the field.

In the 2003 and 2004 potato experiment, the treatment application and yield measurements were field-wide. Thus, we were able to obtain four interpolated N response yield maps utilizing the spatial correlation in the data–one for each treatment–for each year (Fig. 7). These N response yield maps were created by interpolating individual treatment responses (i.e., data from every fourth unit or every 12 m) over the entire field. In 2003, for example, the interpolated yield response to no fertilizer application (0 kg N $ha^{-1}$) showed the majority of the field yielded between 10 and 20 t $ha^{-1}$. In the northern portion of the field, from 100 to 120 m, the interpolated yield decreased to between 0 and 10 t $ha^{-1}$. This pattern became more prominent as the treatment application rate increased. Although the yield response in the southern part of the field increased to 30–40 t $ha^{-1}$ at a maximum application rate (280 kg N $ha^{-1}$), the low-yield response in the northern part of the field did not increase beyond 20 t $ha^{-1}$. The general pattern of spatial yield response was similar in 2004 with high yield responses in the south end of the field and low yields in the north end. Again maximum yield response occurred in the south part of the field and reached a maximum of around 50 t $ha^{-1}$, but was associated with the intermediate 112 N $ha^{-1}$ application rate. The yield response in the area between 100 and 120 m, reached a maximum of 20–30 t $ha^{-1}$ at the 56 kg N $ha^{-1}$ application rate, and began to decrease with additional fertilizer. As in

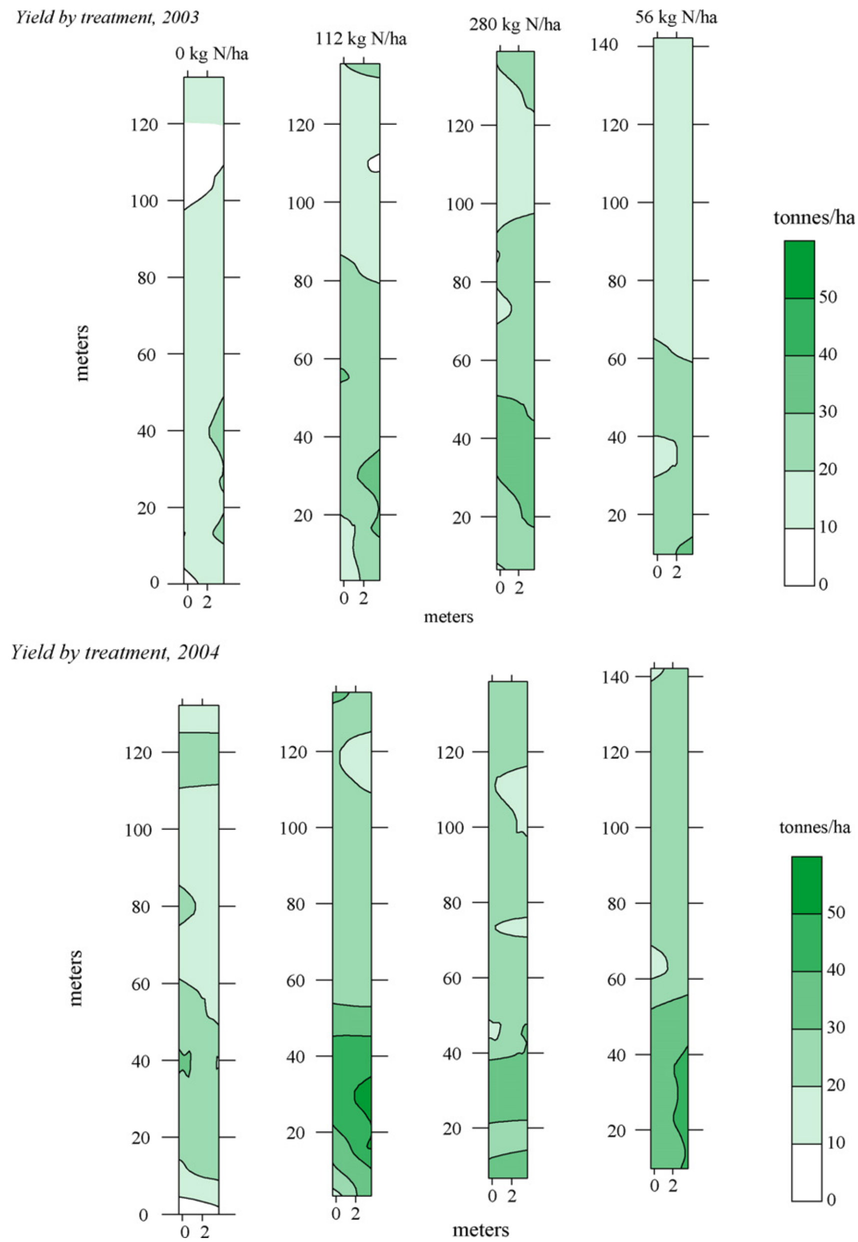


**Fig. 7.** The interpolated distribution of yield for 2003 and 2004 for each level of nitrogen treatment. Interpolation utilized only those data points with the same treatment (i.e., every fourth data point). The maps display the possible yield distribution had the field been treated with only one level of nitrogen.

2003, little if any significant yield response was evident in the north end of the field (110–120 m). Such temporal persistence of crop response to N was reported also by Shahandeh et al. (2005). It is noteworthy that the persistent low-yield area (100–120 m in Fig. 7) did not have a strong response to even high levels of N application. And, low clay contents were observed in that same area (Fig. 3).

The layout of treatments in the landscape affects the ability to characterize error in treatment response. Both Cassel et al. (1988) and Hoosbeek et al. (1998) used classical statistical designs employing randomization, replication and blocking. Hoosbeek et al. (1998) used simulation to show that a spatially randomized design rather than clustered blocking resulted in lower prediction variances across the catena. One advantage of using the sinusoidal treatment pattern as done in our study is that the pattern of the response can be compared to the pattern of the treatment. This allows a spatial interpretation of how the crop responds to a range in application rates rather than only one or two.

This research was carried out on a small scale relative to larger fields that are 10–20 ha in size. As field size increases, it becomes more difficult to sample soil properties at enough locations to adequately characterize spatial variability. However the use of combines along with yield monitors can provide yield data at very small scales and with wide coverage (Sadler et al., 1998). Yield data can be useful diagnostic data to infer the distribution of soil properties at large scales (Timlin et al., 2001; Morgan et al., 2003). Using fertilizer application with a global positioning system one can apply fertilizers in different patterns such as the sinusoidal pattern utilized here. The variance in the pattern of the yield in response to the applied fertilizer pattern will be indicative of the soil and landscape properties that affect yield.

## 4. Conclusions

Adjusting field-wide potato yield data with a random field linear model accounting for spatially correlated errors resulted in less distinct responses to N fertilization application, as shown by nitrogen response curves. These adjusted yields may more accurately represent mean yield response and may partially account for the discrepancy, cited earlier, between research and practical farm yields. These results were complemented by an examination of the spatial distribution of yield and correlated field properties. Within the field, there were substantial differences in yield response to N treatment, but those differences depended on field position. The spatial distribution of potato yield response was partially explained by soil clay content, but not other measured field properties (PAWC and initial soil nitrate), as illustrated by residual distribution.

The difference in magnitude of yield between 2003 and 2004 were attributed to year-to-year weather differences especially early season temperatures. It is notable that although the magnitude of potato yield differed between years, the spatial distribution of yield each year was the same. Nevertheless, this year difference highlighted the limitations and complementarities between spatial field properties and physiologic plant response to management (e.g., timing of plant fertilizer application) and environmental (climatic) conditions in the soil–plant–atmosphere continuum. This is important not only for inference and understanding, but for prediction and decision making for both current and future conditions.

The potato yield response for each N level was interpolated to provide a field-level response map as if only one fertilizer level was applied to the field. The maps showed an area of the field, for example, that did not have a strong response to even high levels of N. This means that additional N to obtain a response would only lead to excessive loss of N from the soil. Such areas would probably benefit from small but frequent applications of N to time application with optimal plant uptake.

While the experimental field was not large, the experimental design and analysis allowed for the exploration of the role of spatial variability in agricultural experimentation. The design and analysis addressed the need for new approaches to this issue and still allowed for traditional inference at the whole-field scale. The results were particular to the crop, soil, and climate tested, but suggest further methodological applicability for other crops in other settings.

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## References

Alva, A., 2004a. Potato nitrogen management. J. Veg. Crop Prod. 10 (1), 97–130.
Alva, A., 2004b. Effects of pre-plant and in-season nitrogen management practices on tuber yield and quality of two potato cultivars. J. Veg. Crop Prod. 10 (2), 43–60.
Anderson, D.L., Portier, K.M., Obreza, T.A., Collins, M.E., Pitts, D.J., 1999. Tree regression analysis to determine effects of soil variability on sugarcane yields. Soil Sci. Soc. Am. J. 63, 592–600.
Balasubramanian, V., Alves, B., Aulakh, M., Behunda, M., Cai, Z., Drinkwater, L., Mugendi, D., van Kessel, C., Oenema, O., 2004. Crop, environmental, and management factors affecting nitrogen use efficiency. In: Mosier, A.R., et al. (Eds.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. Island Press, Washington, DC, pp. 19–33.
Bélanger, G., Walsh, J.R., Richards, J.E., Milburn, P.H., Ziadi, N., 2000a. Yield response of two potato cultivars to supplemental irrigation and N fertilization in New Brunswick. Am. J. Potato Res. 77, 11–21.
Bélanger, G., Walsh, J.R., Richards, J.E., Milburn, P.H., Ziadi, N., 2000b. Comparison of three statistical models describing potato yield response to nitrogen fertilizer. Agron. J. 92, 902–908.
Bélanger, G., Walsh, J.R., Richards, J.E., Milburn, P.H., Ziadi, N., 2001. Predicting nitrogen fertilizer requirements of potatoes in Atlantic Canada with soil nitrate determinations. Can. J. Soil Sci. 81, 535–544.
Brownie, C., Gumpertz, M.L., 1997. Validity of spatial analyses for large field trials. J. Agr. Biol. Environ. Stat. 2, 1–23.
Cassel, D.K., Upchurch, D.R., Anderson, S.H., 1988. Using regionalized variables to estimate field variability of corn yield for four tillage regimes. Soil Sci. Soc. Am. J. 52, 222–228.
Cassman, K.G., Dobermann, A., Waters, D.T., 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31, 132–140.
Clifford, P., Richardson, S., Hémon, D., 1989. Assessing the significance of the correlation between two spatial processes. Biometrics 45, 123–134.
Dobermann, A., Cassman, K.C., 2004. Environmental dimensions of fertilizer nitrogen: what can be done to increase nitrogen use efficiency and ensure global food security? In: Mosier, A.R., et al. (Eds.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. Island Press, Washington, DC, pp. 261–278.
Edmondson, R.N., 2005. Past developments and future opportunities in the design and analysis of crop experiments. J. Agric. Sci. 143, 27–33.
Eghball, B., Schepers, J.S., Hegahgan, M., Schlemmer, M.R., 2003. Spatial and temporal variability of soil nitrate and corn yield: multifractal analysis. Agron. J. 95, 339–346.
Errebhi, M., Rosen, C.J., Gupta, S.C., Birong, D.E., 1998. Potato yield response and nitrate leaching as influenced by nitrogen management. Agron. J. 90, 10–15.
Firman, D.M., O'Brien, P.J., Allen, E.J., 1995. Appearance and growth of individual leaves in the canopies of several potato cultivars. J. Agric. Sci. 125, 379–394.
Fox, R.L., 1972. Symptoms of plant nutritional deficiency—visual symptoms and incipient malnutrition. In: Illustrated Concepts of Tropical Agriculture, Department of Agronomics and Soils, University of Hawaii, No. 4.
Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. 2nd ed. ASA and SSSA, Madison, WI, pp. 383–411.
Golden Software, Inc. 2002. Surfer User's Guide. Ver. 8.0. Golden, CO.
Gotway, C.A., Cressie, N.A.C., 1990. A spatial analysis of variance applied to soil–water infiltration. Water Resour. Res. 26, 2695–2703.
Griffin, T.W., Lambert, D.M., Lowenberg-DeBoer, J.M., 2005. Testing appropriate on-farm trial designs and statistical methods for precision farming: a simulation approach. In: D.J. Mulla et al. (Ed.). Proceedings of the International Conference on Precision Agriculture and Other Precision Resources Management, 7th, Minneapolis, MN. July 25–28, 2004 [CD-ROM computer file]. ASA, CSSA, and SSSA, Madison, WI.
Griffith, D.A., Layne, L.J., 1999. A Casebook for Spatial Statistical Data Analysis: A Compilation of Analyses of Different Thematic Data Sets. Oxford University Press, New York.
Gusmão, L., 1986. Inadequacy of blocking in cultivar yield trials. Theor. Appl. Genet. 72, 98–104.
Hansen, V.E., Israelsen, O.W., Stringham, G.E., 1980. Irrigation Principles and Practices. Wiley, New York.
Heffner, R.A., Butler IV, M.H., Reilly, C.K., 1996. Pseudoreplication revisited. Ecology 77, 2558–2562.
Hong, N., White, J.G., Gumpertz, M.L., Weisz, R., 2005. Spatial analysis of precision agriculture treatments in randomized complete blocks: guidelines for covariance model selection. Agron. J. 97, 1082–1096.
Hoosbeek, M.R., Stein, A., van Reuler, H., Janssen, B.H., 1998. Interpolation of agronomic data from plot to field scale: using a clustered versus a spatially randomized block design. Geoderma 81, 265–280.
Legendre, P., Dale, M.R.T., Fortin, M.-J., Gurevitch, J., Hohn, M., Myers, D., 2002. The consequences of spatial structure for the design and analysis of ecological field surveys. Ecography 25, 601–615.
Lin, C.S., Binns, M.R., Voldeng, H.D., Guillemette, R., 1993. Performance of randomized block design in field experiments. Agron. J. 85, 168–171.
Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Institute, Cary, NC.
Matalas, N.C., Langbein, W.B., 1962. Information content of the mean. J. Geophys. Res. 67, 3441–3448.
Matheron, G., 1963. Principles of Geostatistics. Econ. Geol. 58, 1246–1266.
Matson, P., Lohse, K.A., Hall, S.J., 2002. The globalization of nitrogen deposition: consequences for terrestrial ecosystems. Ambio 31, 113–119.
Morgan, C.L.S., Norman, J.M., Lowery, B., 2003. Estimating plant-available water across a field with an inverse yield model. Soil Sci. Soc. Am. J. 67 (2), 620–629.
Mosier, A.R., Syers, J.K., Freney, J.R., 2004. Nitrogen fertilizer: an essential component of increased food, feed, and fiber production. In: Mosier, A.R., et al. (Eds.), Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment. Island Press, Washington, DC, pp. 3–15.
Mulla, D.J., Bhatti, A.U., Kunkel, R., 1990. Methods for removing spatial variability from field research trials. In: Advances in Soil Science, vol. 13, Springer-Verlag, New York Inc., pp. 201–213.

Mulla, D.J., McBratney, A.B., 2002. Soil spatial variability. In: Warrick, A.W. (Ed.), Soil Physics Companion. CRC Press, Boca Raton, FL, pp. 343–373.
Mulvaney, R.L., 1996. Nitrogen—inorganic forms. In: Sparks, D.L., et al. (Eds.), Methods of Soil Analysis. Part 3. ASA and SSSA, Madison, WI, pp. 1123–1184.
Nielsen, D.R., Wendroth, O., 2003. Spatial and Temporal Statistics: Sampling Field Soils and their Vegetation. Catena Verlag GMBH, Reiskirchen, Germany.
Or, D., Wraith, M., 2002. Soil water content and water potential relationships. In: Warrick, A.W. (Ed.), Soil Physics Companion. CRC Press LLC, Boca Raton, FL, pp. 49–84.
Pachepsky, Ya, Timlin, D.J., Rawls, W.J., 2001. Soil water retention as related to topographic variables. Soil Sci. Soc. Am. J. 65, 1787–1795.
Peterson, G.A., Westfall, D.G., Cole, C.V., 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57, 1354–1360.
Redulla, C.A., Davenport, J.R., Evans, R.G., Hattendorf, M.J., Alva, A.K., Boydston, R.A., 2002. Relating potato yield and quality to field scale variability in soil characteristics. Am. J. Potato Res. 79, 317–323.
Sadler, E.J., Busscher, W.J., Bauer, P.J., Karlen, D.L., 1998. Spatial scale requirements for precision farming: a case study in the southeastern USA. Agron. J. 90, 191–197.
Sadler, E.J., Camp, C.R., Evans, D.E., Millen, J.A., 2002. Spatial variation of corn response to irrigation. Trans. ASAE 45 (6), 1869–1881.
Scharf, P.C., 2001. Soil and plant tests to predict optimum nitrogen rates for corn. J. Plant Nutr. 24 (6), 805–826.
Scharf, P.C., Kitchen, N.R., Sudduth, K.A., Davis, J.G., Hubbard, V.C., Lory, J.A., 2005. Field-scale variability in optimal nitrogen fertilizer rate for corn. Agron. J. 97, 452–461.
Shahandeh, H., Wright, A.L., Hons, F.M., Lascano, R.J., 2005. Spatial and temporal variation of soil nitrogen parameters related to soil texture and corn yield. Agron. J. 97, 772–782.
Singh, M., Malhotra, R.S., Ceccarelli, S., Sarker, A., Grando, S., Erskine, W., 2003. Spatial variability models to improve dryland field trials. Expl. Agric. 39, 151–160.
Struik, P.C., Ewing, E.E., 1995. Crop physiology of potato: Responses to photoperiod and temperature relevant to crop modeling. In: Haverkort, A.J., MacKerron, D.K.L. (Eds.), Potato Ecology and Modeling of Crops under Conditions Limiting Growth. Kluwer Academic Publishers, Boston, MA, pp. 19–40.
Timlin, D.J., Pachepsky, Ya., Snyder, V.A., Bryant, R.B., 1998. Spatial and temporal variability of corn grain yield on a hill slope. Soil Sci. Soc. Am. J. 62, 764–773.
Timlin, D.J., Pachepsky, Ya., Snyder, V.A., Bryant, R.B., 2001. Water budget approach to quantify corn grain yields under variable rooting depths. Soil Sci. Soc. Am. J. 65, 1219–1226.
van Es, H.M., van Es, C.L., 1993. Spatial nature of randomization and its effect on the outcome of field experiments. Agron. J. 85, 420–428.
Vos, J., 1999. Split nitrogen application in potato: Effects on accumulation of nitrogen and dry matter in the crop and on the soil nitrogen budget. J. Agric. Sci. 133, 263–374.
Vos, J., Biemond, H., 1992. Effects of nitrogen on the development and growth of the potato plant. 1. Leaf appearance, expansion growth, life spans of leaves and stem branching. Ann. Bot. 70, 27–35.
Zimmerman, D.L., Harville, D.A., 1991. A random field approach to the analysis of field-plot experiments and other spatial experiments. Biometrics 47, 223–239.